Ferromagnetism and Spontaneous Vortex Formation in Superconducting $ErNi_2B_2C$

The competition between magnetic order and superconductivity has had an interesting history. The first examples of true long range magnetic order coexisting with superconductivity were provided by the ternary Chevrel-phase superconductors and related compounds. The magnetic ordering temperatures were all low (≈ 1 K), indicating that dipolar interactions dominate the energetics of the magnetic system. Similar behavior is found for the rare earth ordering in the hole-doped cuprates [1]. The first systems where exchange clearly dominates the magnetic energetics were provided by the electron-doped cuprates [1], followed by the borocarbides of central interest here [2].

Among these systems, the rare and interesting situation where ferromagnetic interactions are present has attracted special attention because of the competitive nature between the superconducting screening and the internally generated magnetic field. In the Chevrel phase materials this competition gives rise to long wavelength oscillatory magnetic states and/or reentrant superconductivity. Recently, superconducting $ErNi_2B_2C$ (T_c = 11 K) appeared to develop a net magnetization below 2.3 K, well below the onset of long range spin-density-wave order at T_N = 6 K. We have carried out a comprehensive study of the magnetic order and vortex structure in this material, and directly demonstrated that this transition does indeed correspond to the development of a net atomic magnetization that coexists with superconductivity, and this results in the spontaneous formation of vortices in the system [3].

Superconducting $ErNi_2B_2C$ orders magnetically at 6 K into a transversely polarized spin density wave structure [2, 3], with the modulation wave vector δ along the *a* axis and the spins along the *b* direction. A portion of a scan along the *a* axis is shown in Fig. 1 at three temperatures. The initial ordering is a simple spin density wave as shown in the schematic, with an incommensurate modulation of $\delta \cong 0.55\ a^*$ ($a^* = 2\pi/a$). At 2.4 K additional higher-order peaks become observable as the magnetic structure squares up as indicated schematically at the bottom of Fig. 1. These peaks are all odd-order harmonics as expected for a square-wave magnetic structure.

Below the weak ferromagnetic transition (T_{WFM}) at 2.3 K, the data (Fig. 1) indicate that a new series of peaks has developed, which are *even* harmonics of the fundamental wave vector. Polarized neutron measurements unambiguously establish that both the odd-order peaks *and* the even-order peaks are magnetic in origin.

The integrated intensities of the odd- and even-order harmonics are shown in Fig. 2 as a function of *T*. The even-order peaks abruptly develop below 2.3 K, concomitant with the development of the new (weak) ferromagnetism at T_{WFM}.

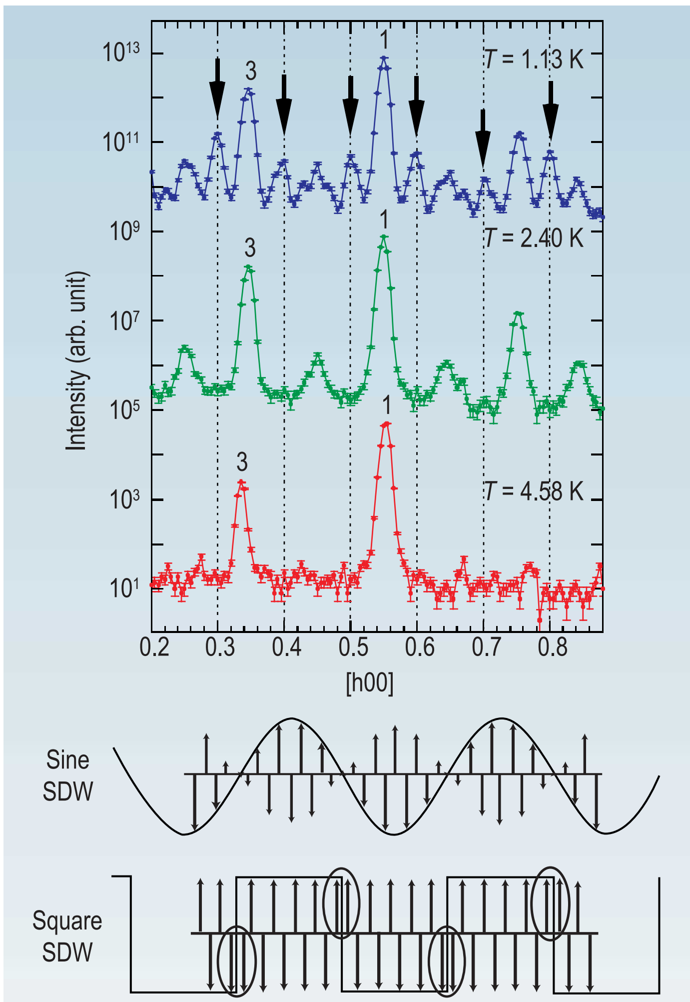

FIGURE 1. Scan along the [h00] direction at *T* = 1.3 K, 2.4 K, and 4.58 K. The data have been offset for clarity. Above the weak ferromagnetic transition at 2.3 K we observe the fundamental peak at ≈ 0.55 along with odd-order harmonics, while below a new set of even harmonics develops (arrows). Also shown is a schematic of the spin density wave order for *T* just below T_N, and the (undistorted) wave when it squares up.

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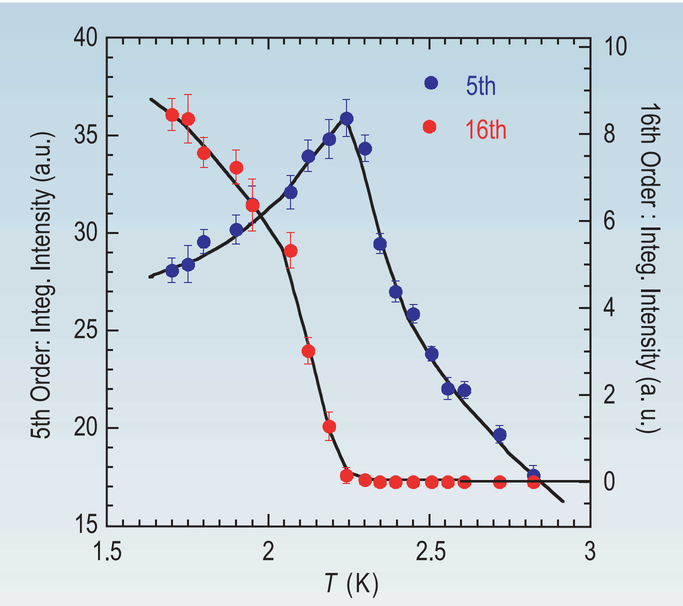

FIGURE 2. Integrated intensities of the odd (blue circles) and even (red circles) order harmonics as a function of *T*.

There is a substantial thermal hysteresis associated with the weak ferromagnetic transition, suggesting that this transition is first order in nature.

The present neutron results demonstrate that a net magnetization develops in $ErNi_2B_2C$ in the magnetically ordered state at low temperatures, making this the first such "ferromagnetic-superconductor" since $HoMo_6S_8$, $HoMo_6Se_8$, and $ErRh_4B_4$. For $ErNi_2B_2C$ the net magnetization is much smaller than for these earlier systems, which allows coexistence with superconductivity over an extended *T* range. This presents the intriguing possibility that in an applied field vortices will form spontaneously when this net atomic magnetization is present. The small angle scattering data of the vortex structure (Fig. 3 top) show that the lattice has the expected spacing at lower applied fields. At higher fields, as the field begins to penetrate, vortices spontaneously form in addition to those expected from the applied field alone, increasing the vortex density and shifting the vortex peak. The *T* dependence of this shift (Fig. 3 bottom) makes it clear that this behavior is directly related to onset of the net magnetization in the system. It is also interesting to note that the vortex pinning is enhanced in both magnetic phases, which may prove useful in high current applications of superconductors.

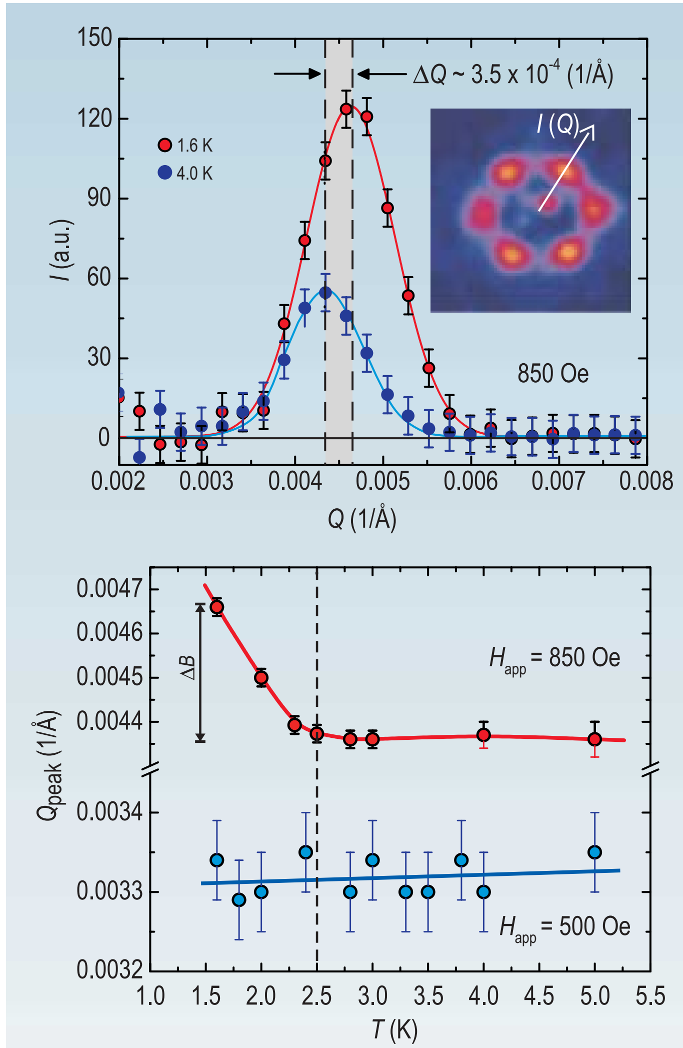

FIGURE 3. Intensity of the vortex scattering vs. wave vector *Q* at 850 Oe above and below the weak ferromagnetic transition. The shift in the peak position demonstrates that additional vortices spontaneously form at low temperatures. The temperature dependence (bottom) shows that this spontaneous vortex formation is directly related to the weak ferromagnetic transition.

References

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